

CHAPTER 5

REACTOR COOLANT SYSTEM AND CONNECTED SYSTEMS

5.1 Summary Description

This section describes the reactor coolant system (RCS) and includes a schematic flow diagram of the reactor coolant system (Figure 5.1-1), an isometric view of the reactor coolant loops and major components (Figure 5.1-2), a sketch of the loop layout (Figure 5.1-3), and a sketch of the elevation of the reactor coolant system (Figure 5.1-4, sheets 1 and 2). The piping and instrumentation diagram (Figure 5.1-5, sheets 1, 2, and 3) shows additional details of the design of the reactor coolant system.

5.1.1 Design Bases

The performance and safety design bases of the reactor coolant system and its major components are interrelated. These design bases are listed as follows:

- The reactor coolant system transfers to the steam and power conversion system the heat produced during power operation as well as the heat produced when the reactor is subcritical, including the initial phase of plant cooldown.
- The reactor coolant system transfers to the normal residual heat removal system the heat produced during the subsequent phase of plant cooldown and cold shutdown.
- During power operation and normal operational transients (including the transition from forced to natural circulation), the reactor coolant system heat removal maintain fuel condition within the operating bounds permitted by the reactor control and protection systems.
- The reactor coolant system provides the water used as the core neutron moderator and reflector conserving thermal neutrons and improving neutron economy. The reactor coolant system also provides the water used as a solvent for the neutron absorber used in chemical shim reactivity control.
- The reactor coolant system maintains the homogeneity of the soluble neutron poison concentration and the rate of change of the coolant temperature so that uncontrolled reactivity changes do not occur.
- The reactor coolant system pressure boundary accommodates the temperatures and pressures associated with operational transients.
- The reactor vessel supports the reactor core and control rod drive mechanisms.
- The pressurizer maintains the system pressure during operation and limits pressure transients. During the reduction or increase of plant load, the pressurizer accommodates volume changes in the reactor coolant.

- The reactor coolant pumps supply the coolant flow necessary to remove heat from the reactor core and transfer it to the steam generators.
- The steam generators provide high-quality steam to the turbine. The tubes and tubesheet boundary prevent the transfer of radioactivity generated within the core to the secondary system.
- The reactor coolant system piping contains the coolant under operating temperature and pressure conditions and limits leakage (and activity release) to the containment atmosphere. The reactor coolant system piping contains demineralized and borated water that is circulated at the flow rate and temperature consistent with achieving the reactor core thermal and hydraulic performance.
- The reactor coolant system is monitored for loose parts, as described in subsection 4.4.6.
- Applicable industry standards and equipment classifications of reactor coolant system components are identified in Tables 3.2-1 and 3.2-3 of subsection 3.2.2.
- The reactor vessel head is equipped with suitable provisions for connecting the head vent system, which meets the requirements of 10 CFR 50.34 (f)(2)(vi) (TMI Action Item II.B.1). (See subsection 5.4.12.)
- The pressurizer surge line and each loop spray line connected with the reactor coolant system are instrumented with resistance temperature detectors (RTDs) attached to the pipe to detect thermal stratification.

5.1.2 Design Description

Figure 5.1-1 shows a schematic of the reactor coolant system. Table 5.1-1 provides the principal pressures, temperatures, and flow rates of the system at the locations noted in Figure 5.1-1 under normal steady-state, full-power operating conditions. These parameters are based on the best-estimate flow at the pump discharge. Table 5.1-2 contains a summary of nominal system design and operating parameters under normal steady-state, full-power operating conditions. These parameters are based on the best-estimate conditions at nominal full power. The reactor coolant system volume under these conditions is also provided.

The reactor coolant system consists of two heat transfer circuits, each with a steam generator, two reactor coolant pumps, and a single hot leg and two cold legs for circulating reactor coolant. In addition, the system includes the pressurizer, interconnecting piping, valves, and instrumentation for operational control and safeguards actuation. All reactor coolant system equipment is located in the reactor containment.

During operation, the reactor coolant pumps circulate pressurized water through the reactor vessel then the steam generators. The water, which serves as coolant, moderator, and solvent for boric acid (chemical shim control), is heated as it passes through the core. It is transported to the steam generators where the heat is transferred to the steam system. Then it is returned to the reactor vessel by the pumps to repeat the process.

The reactor coolant system pressure boundary provides a barrier against the release of radioactivity generated within the reactor and is designed to provide a high degree of integrity throughout operation of the plant.

The reactor coolant system pressure is controlled by operation of the pressurizer, where water and steam are maintained in equilibrium by the activation of electrical heaters or a water spray, or both. Steam is formed by the heaters or condensed by the water spray to control pressure variations due to expansion and contraction of the reactor coolant.

Spring-loaded safety valves are installed above and connected to the pressurizer to provide overpressure protection for the reactor coolant system. These valves discharge into the containment atmosphere. Three stages of reactor coolant system automatic depressurization valves are also connected to the pressurizer. These valves discharge steam and water through spargers to the in-containment refueling water storage tank (IRWST) of the passive core cooling system (PXS). Most (initially all) of the steam and water discharged to the spargers is condensed and cooled by mixing with the water in the tank.

The fourth-stage automatic depressurization valves are connected by two redundant paths to each reactor coolant loop hot leg and discharge directly to the containment atmosphere.

The reactor coolant system is also served by a number of auxiliary systems, including the chemical and volume control system (CVS), the passive core cooling system (PXS), the normal residual heat removal system (RNS), the steam generator system (SGS), the primary sampling system (PSS), the liquid radwaste system (WLS), and the component cooling water system (CCS).

The reactor coolant system includes the following:

- The reactor vessel, including control rod drive mechanism housings.
- The reactor coolant pumps, consisting of four sealless pumps that pump fluid through the entire reactor coolant and reactor systems. Two pumps are coupled with each steam generator.
- The portion of the steam generators containing reactor coolant, including the channel head, tubesheet, and tubes.
- The pressurizer which is attached by the surge line to one of the reactor coolant hot legs. With a combined steam and water volume, the pressurizer maintains the reactor system within a narrow pressure range.
- The safety and automatic depressurization system valves.
- The reactor vessel head vent isolation valves.
- The interconnecting piping and fittings between the preceding principal components.
- The piping, fittings, and valves leading to connecting auxiliary or support systems.

The piping and instrumentation diagram of the reactor coolant system (Figure 5.1-5) shows the extent of the systems located within the containment and the interface between the reactor coolant system and the secondary (heat utilization) system.

Figures 5.1-3 and 5.1-4 show the plan and section of the reactor coolant loops. These figures show reactor coolant system components in relationship to supporting and surrounding steel and concrete structures. The figures show the protection provided to the reactor coolant system by its physical layout.

5.1.3 System Components

The major components of the reactor coolant system are described in the following subsections. Additional details of the design and requirements of these components are found in other sections of this safety analysis report.

5.1.3.1 Reactor Vessel

The reactor vessel is cylindrical, with a hemispherical bottom head and removable, flanged, hemispherical upper head. The vessel contains the core, core support structures, control rods, and other parts directly associated with the core. The vessel interfaces with the reactor internals, the integrated head package, and reactor coolant loop piping and is supported on the containment building concrete structure.

The design of the AP1000 reactor vessel closely matches the existing vessel designs of Westinghouse three-loop plants. New features for the AP1000 have been incorporated without departing from the proven features of existing vessel designs.

The vessel has inlet and outlet nozzles positioned in two horizontal planes between the upper head flange and the top of the core. The nozzles are located in this configuration to provide an acceptable cross-flow velocity in the vessel outlet region and to facilitate optimum layout of the reactor coolant system equipment. The inlet and outlet nozzles are offset, with the inlet positioned above the outlet, to allow mid-loop operation for removal of a main coolant pump without discharge of the core.

Coolant enters the vessel through the inlet nozzles and flows down the core barrel-vessel wall annulus, turns at the bottom, and flows up through the core to the outlet nozzles.

5.1.3.2 AP1000 Steam Generator

The AP1000 steam generator (SG) is a vertical shell and U-tube evaporator with integral moisture separating equipment. The basic steam generator design and features have been proven in tests and in previous steam generators including replacement steam generator designs.

Design enhancements include nickel-chromium-iron Alloy 690 thermally treated tubes on a triangular pitch, improved antivibration bars, single-tier separators, enhanced maintenance features, and a primary-side channel head design that allows for easy access and maintenance by robotic tooling. The AP1000 steam generator employs tube supports utilizing a broached hole

support plate design. All tubes in the steam generator are accessible for sleeving, if necessary. The design enhancements are based on proven technology.

The basic function of the AP1000 steam generator is to transfer heat from the single-phase reactor coolant water through the U-shaped heat exchanger tubes to the boiling, two-phase steam mixture in the secondary side of the steam generator. The steam generator separates dry, saturated steam from the boiling mixture, and delivers the steam to a nozzle from which it is delivered to the turbine. Water from the feedwater system replenishes the steam generator water inventory by entering the steam generator through a feedwater inlet nozzle and feeding.

In addition to its steady-state performance function, the steam generator secondary side provides a water inventory which is continuously available as a heat sink to absorb primary side high temperature transients.

5.1.3.3 Reactor Coolant Pumps

The AP1000 reactor coolant pumps are high-inertia, high-reliability, low-maintenance, sealless pumps of either canned motor or wet winding motor design that circulate the reactor coolant through the reactor vessel, loop piping, and steam generators. The pumps are integrated into the steam generator channel head.

The integration of the pump suction into the bottom of the steam generator channel head eliminates the cross-over leg of coolant loop piping; reduces the loop pressure drop; simplifies the foundation and support system for the steam generator, pumps, and piping; and reduces the potential for uncovering of the core by eliminating the need to clear the loop seal during a small loss of coolant accident.

The AP1000 design uses four pumps. Two pumps are coupled with each steam generator.

Each AP1000 reactor coolant pump is a vertical, single-stage centrifugal pump designed to pump large volumes of main coolant at high pressures and temperatures. Because of its sealless design, it is more tolerant of off-design conditions that could adversely affect shaft seal designs. The main impeller attaches to the rotor shaft of the driving motor, which is an electric induction motor.

Primary coolant circulates between the stator and rotor which obviates the need for a seal around the motor shaft. Additionally, the motor bearings are lubricated by primary coolant. The motor is thus an integral part of the pump. The basic pump design has been proven by many years of service in other applications.

The pump motor size is minimized through the use of a variable frequency drive to provide speed control in order to reduce motor power requirements during pump startup from cold conditions. The variable frequency drive is used only during heatup and cooldown when the reactor trip breakers are open. During power operations, the drive is isolated and the pump is run at constant speed.

To provide the rotating inertia needed for flow coast-down, bi-metallic flywheel assemblies are attached to the pump shaft.

5.1.3.4 Primary Coolant Piping

Reactor coolant system piping is configured with two identical main coolant loops, each of which employs a single 31-inch inside diameter hot leg pipe to transport reactor coolant to a steam generator. The two reactor coolant pump suction nozzles are welded directly to the outlet nozzles on the bottom of the steam generator channel head. Two 22-inch inside diameter cold leg pipes in each loop (one per pump) transport reactor coolant back to the reactor vessel to complete the circuit.

The loop configuration and material have been selected such that pipe stresses are sufficiently low for the primary loop and large auxiliary lines to meet the requirements to demonstrate "leak-before-break." Thus, pipe rupture restraints are not required, and the loop is analyzed for pipe ruptures only for small auxiliary lines that do not meet the leak-before-break requirements.

5.1.3.5 Pressurizer

The AP1000 pressurizer is a principal component of the reactor coolant system pressure control system. It is a vertical, cylindrical vessel with hemispherical top and bottom heads, where liquid and vapor are maintained in equilibrium saturated conditions.

One spray nozzle and two nozzles for connecting the safety and depressurization valve inlet headers are located in the top head. Electrical heaters are installed through the bottom head. The heaters are removable for replacement. The bottom head contains the nozzle for attaching the surge line. This line connects the pressurizer to a hot leg, and provides for the flow of reactor coolant into and out of the pressurizer during reactor coolant system thermal expansions and contractions.

5.1.3.6 Pressurizer Safety Valves

The pressurizer safety valves are spring loaded, self-actuated with back-pressure compensation. Their set pressure and combined capacity is based on not exceeding the reactor coolant system maximum pressure limit during the Level B service condition loss of load transient.

5.1.3.7 Reactor Coolant System Automatic Depressurization Valves

Some of the functions of the AP1000 passive core cooling system (PXS) are dependent on depressurization of the reactor coolant system. This is accomplished by the automatically actuated depressurization valves. The automatic depressurization valves connected to the pressurizer are arranged in six parallel sets of two valves in series opening in three stages.

A set of fourth-stage automatic depressurization valves is connected to each reactor coolant hot leg. Each set of valves consists of two parallel paths of two valves in series.

To mitigate the consequences of the various accident scenarios, the controls are arranged to open the valves in a prescribed sequence based on core makeup tank level and a timer as described in Section 6.3.

5.1.4 System Performance Characteristics

Table 5.1-3 lists the nominal thermal hydraulic parameters of the reactor coolant system. The system performance parameters are also determined for an assumed 10 percent uniform steam generator tube plugging condition.

Reactor coolant flow is established by a detailed design procedure supported by operating plant performance data and component hydraulics experimental data. The procedure establishes a best-estimate flow and conservatively high and low flows for the applicable mechanical and thermal design considerations. In establishing the range of design flows, the procedure accounts for the uncertainties in the component flow resistances and the pump head-flow capability, established by analysis of the available experimental data. The procedure also accounts for the uncertainties in the technique used to measure flow in the operating plant.

Definitions of the four reactor coolant flows applied in various plant design considerations are presented in the following paragraphs.

5.1.4.1 Best-Estimate Flow

The best-estimate flow is the most likely value for the normal full-power operating condition. This flow is based on the best estimate of the fuel, reactor vessel, steam generator, and piping flow resistances, and on the best estimate of the reactor coolant pump head and flow capability. The best-estimate flow provides the basis for the other design flows required for the system and component design. The best-estimate flow and head also define the performance requirement for the reactor coolant pump. Table 5.1-1 lists system pressure losses based on best-estimate flow.

The best-estimate flow analysis is based on extensive experimental data, including accurate flow and pressure drop data from an operating plant, flow resistance measurements from several fuel assembly hydraulics tests, and hydraulic performance measurements from several pump impeller model tests. Since operating plant flow measurements are in close agreement with the calculated best-estimate flows, the flows established with this design procedure can be applied to the plant design with a high level of confidence.

Although the best-estimate flow is the most likely value to be expected in operation, more conservative flow rates are applied in the thermal and mechanical designs.

5.1.4.2 Minimum Measured Flow

The minimum measured flow is specified in the technical specifications as the flow that must be confirmed or exceeded by the flow measurements obtained during plant startup. This is the flow used in reactor core departure from nucleate boiling (DNB) analysis for the thermal design procedure used in the AP1000. In the thermal design procedure methodology for DNB analysis, flow measurement uncertainties are combined statistically with fuel design and manufacturing uncertainties.

The measured reactor coolant flow will most likely differ from the best-estimate flow because of uncertainties in the hydraulics analysis and the inaccuracies in the instrumentation used to measure flow. The measured flow is expected to fall within a range around the best-estimate flow.

The magnitude of the expected range is established by statistically combining the system hydraulics uncertainty with the total flow rate within the expected range, less any excess flow margin that may be provided to account for future changes in the hydraulics of the reactor coolant system.

5.1.4.3 Thermal Design Flow

The thermal design flow is the conservatively low value used for thermal-hydraulic analyses where the design and measurement uncertainties are not combined statistically, and additional flow margin must therefore be explicitly included. The thermal design flow is derived by subtracting the plant flow measurement uncertainty from the minimum measured flow. The thermal design flow is approximately 4.5 percent less than the best-estimate flow. The thermal design flow is confirmed when the plant is placed in operation. Table 5.1-3 provides tabulations of important design parameters based on the thermal design flow.

5.1.4.4 Mechanical Design Flow

Mechanical design flow is the conservatively high flow used as the basis for the mechanical design of the reactor vessel internals, fuel assemblies, and other system components. Mechanical design flow is established at 104 percent of best-estimate flow.

5.1.5 Combined License Information

This section has no requirement for additional information to be provided in support of the Combined License application.

Table 5.1-1					
PRINCIPAL SYSTEM PRESSURES, TEMPERATURES, AND FLOW RATES					
(Nominal Steady-State, Full Power Operating Conditions)					
Location (Fig. 5.1-1)	Description	Fluid	Pressure (psig)	Nominal Temp. (°F)	Flow ^(a) (gpm)
1	Hot Leg 1	Reactor Coolant	2248	610	177,645
2	Hot Leg 2	Reactor Coolant	2248	610	177,645
3	Cold Leg 1A	Reactor Coolant	2310	537.2	78,750
4	Cold Leg 1B	Reactor Coolant	2310	537.2	78,750
5	Cold Leg 2A	Reactor Coolant	2310	537.2	78,750
6	Cold Leg 2B	Reactor Coolant	2310	537.2	78,750
7	Surge Line Inlet	Reactor Coolant	2248	610	-
8	Pressurizer Inlet	Reactor Coolant	2241	653.0	-
9	Pressurizer Liquid	Reactor Coolant	2235	653.0	-
10	Pressurizer Steam	Steam	2235	653.0	-
11	Pressurizer Spray 1A	Reactor Coolant	2310	537.2	1 - 2
12	Pressurizer Spray 1B	Reactor Coolant	2310	537.2	1 - 2
13	Common Spray Line	Reactor Coolant	2310	537.2	2 - 4
14	ADS Valve Inlet	Steam	2235	653.0	-
15	ADS Valve Inlet	Steam	2235	653.0	-

Note:

(a) At the conditions specified.

Table 5.1-2	
NOMINAL SYSTEM DESIGN AND OPERATING PARAMETERS	
General	
Plant design objective, years	60
NSSS power, MWt	3415
Reactor coolant pressure, psia	2250
Reactor coolant liquid volume at power conditions (including 1000 ft ³ pressurizer liquid), ft ³	9600
Loops	
Number of cold legs	4
Number of hot legs	2
Hot leg ID, in.	31
Cold leg ID, in.	22
Reactor Coolant Pumps	
Type of reactor coolant pumps	Sealless
Number of reactor coolant pumps	4
Estimated motor rating, hp	7300
Effective pump power to coolant, MWt	15
Pressurizer	
Number of units	1
Total volume, ft ³	2100
Water volume, ft ³	1000
Spray capacity, gpm	700
Inside diameter, in.	100
Height, in.	503
Steam Generator	
Steam generator power, MWt/unit	1707.5
Type	Vertical U-tube Feeding-type
Number of units	2
Surface area, ft ² /unit	123,540
Shell design pressure, psia	1200
Zero load temperature, °F	557
Feedwater temperature, °F	440
Exit steam pressure, psia	836
Steam flow, lb/hr per steam generator	7.49x10 ⁶
Total steam flow, lb/hr	14.97x10 ⁶

Table 5.1-3

THERMAL-HYDRAULIC PARAMETERS
(Nominal)

Detailed Thermal-Hydraulic Parameters		
Best-Estimate Flow (BEF)	Without Plugging	With 10% Tube Plugging
Flow rate, gpm/loop	157,500	155,500
Reactor vessel outlet temperature, °F	610.0	610.4
Reactor vessel inlet temperature, °F	537.2	536.8
Minimum Measured Flow (MMF)		
Flow rate, gpm/loop	152,775	150,835
Thermal Design Flow (TDF)		
Flow rate, gpm/loop	149,940	148,000
Reactor vessel outlet temperature, °F	611.7	612.2
Reactor vessel inlet temperature, °F	535.5	535.0
Mechanical Design Flow (MDF)		
Flow rate, gpm/flow	163,800	
Best-Estimate Reactor Core and Vessel Thermal-Hydraulic Parameters		Without Plugging
NSSS power, MWt		3415
Reactor power, MWt		3400
Best-Estimate loop flow, gpm/loop		157,500
Best-Estimate vessel flow, lb/hr		120.4x10 ⁶
Best-Estimate core flow, lb/hr		113.3x10 ⁶
Reactor coolant pressure, psia		2250
Vessel/core inlet temperature, °F		537.2
Vessel average temperature, °F		573.6
Vessel outlet temperature, °F		610.0
Average core outlet temperature, °F		614.0
Total core bypass flow, (percent of total flow)		5.9
Core barrel nozzle flow		1.0
Head cooling flow		1.5
Thimble flow		1.9
Cavity bypass flow		1.0
Core shroud cooling flow		0.5

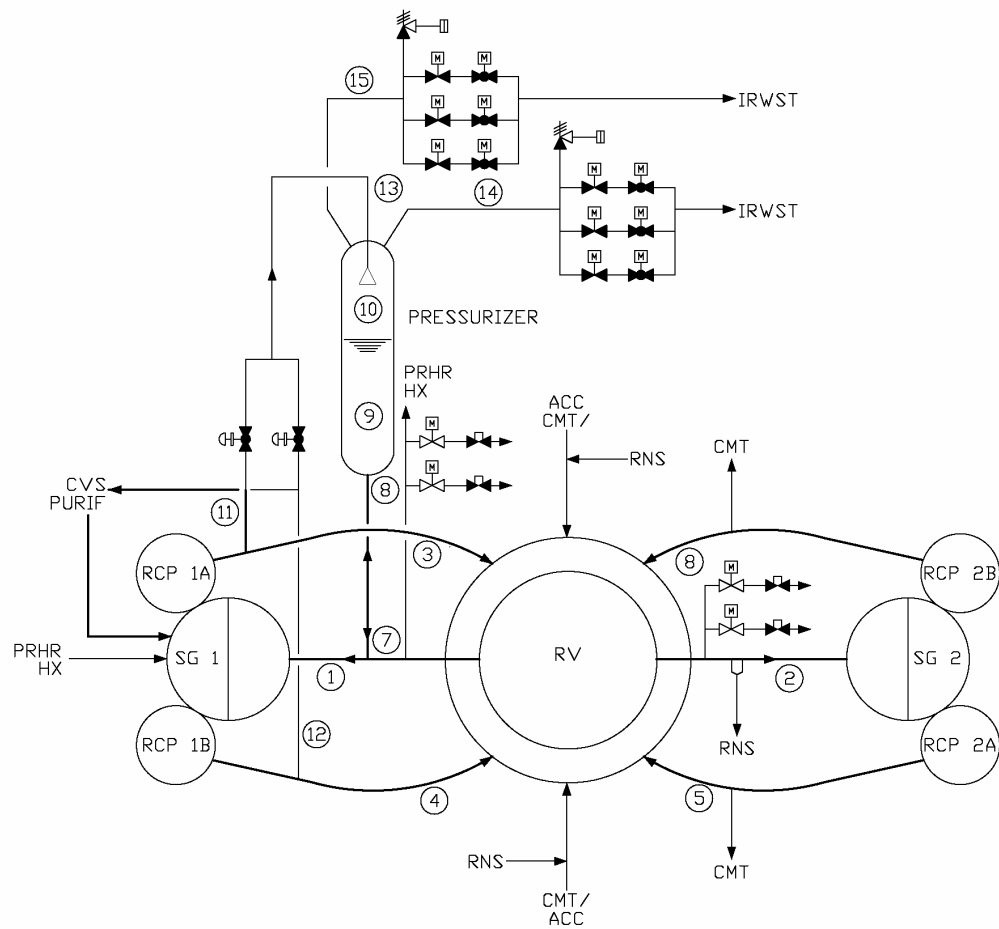


Figure 5.1-1

Reactor Coolant System Schematic Flow Diagram

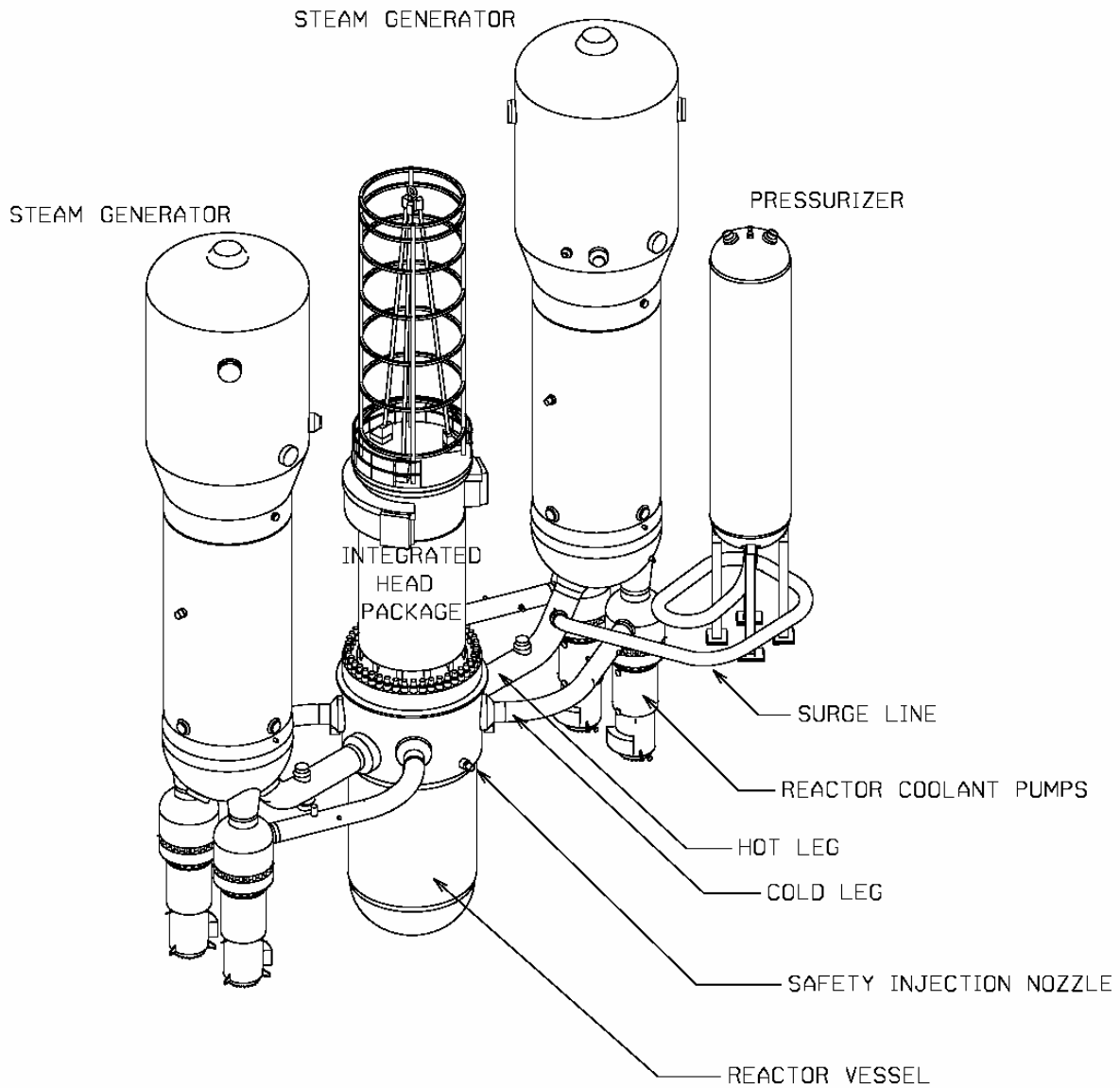


Figure 5.1-2

Reactor Coolant Loops – Isometric View

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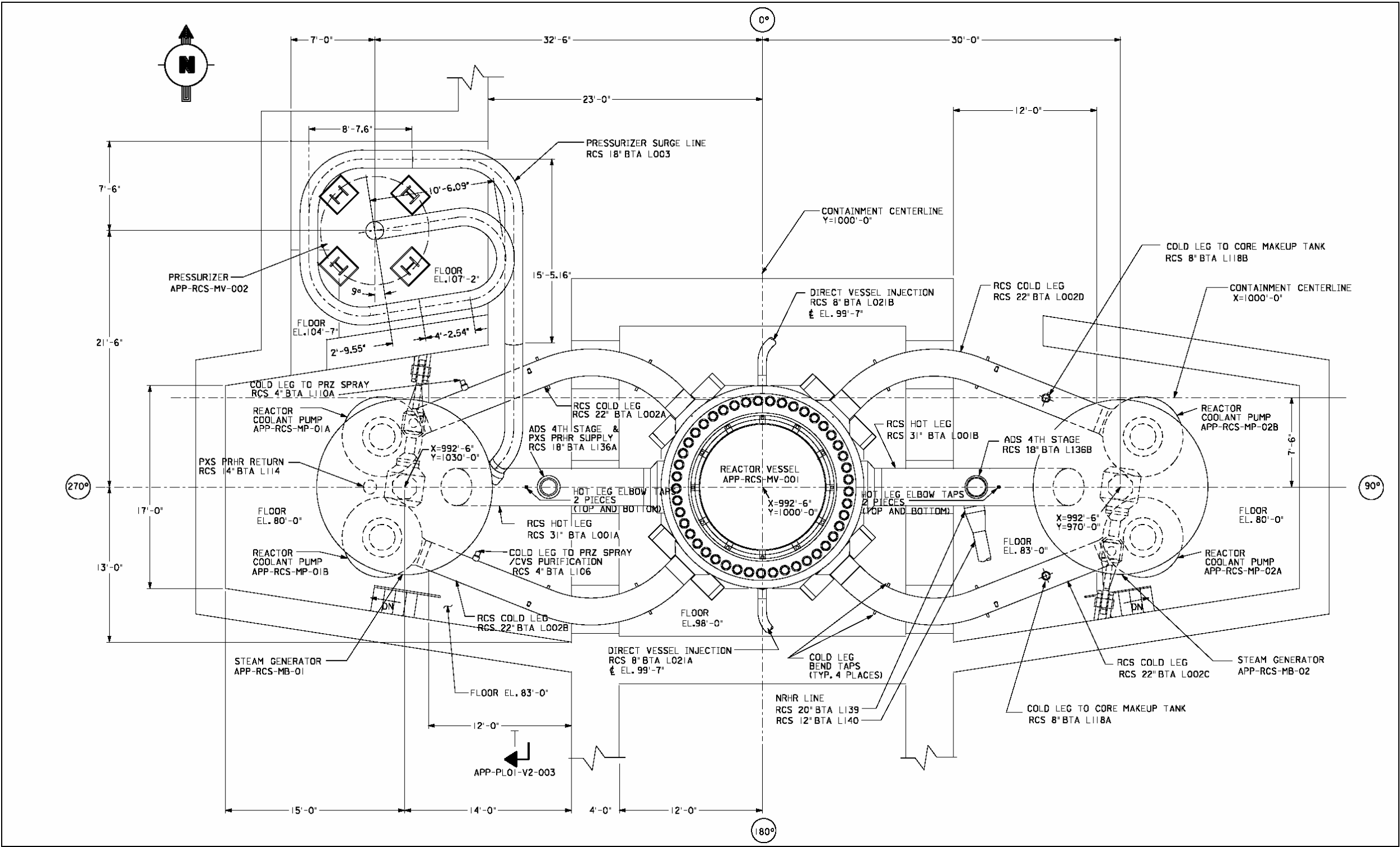


Figure 5.1-3

Reactor Coolant System – Loop Layout

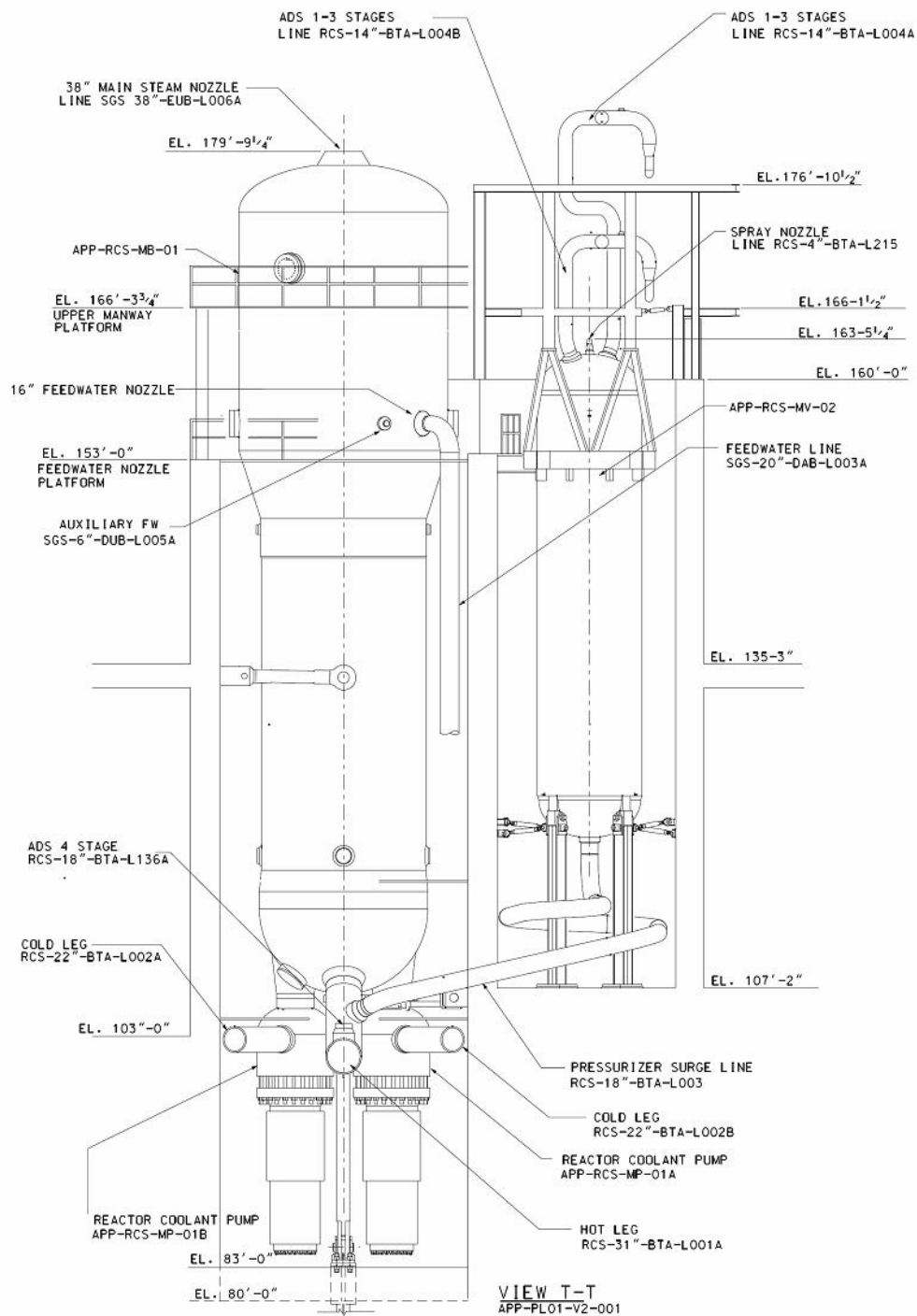
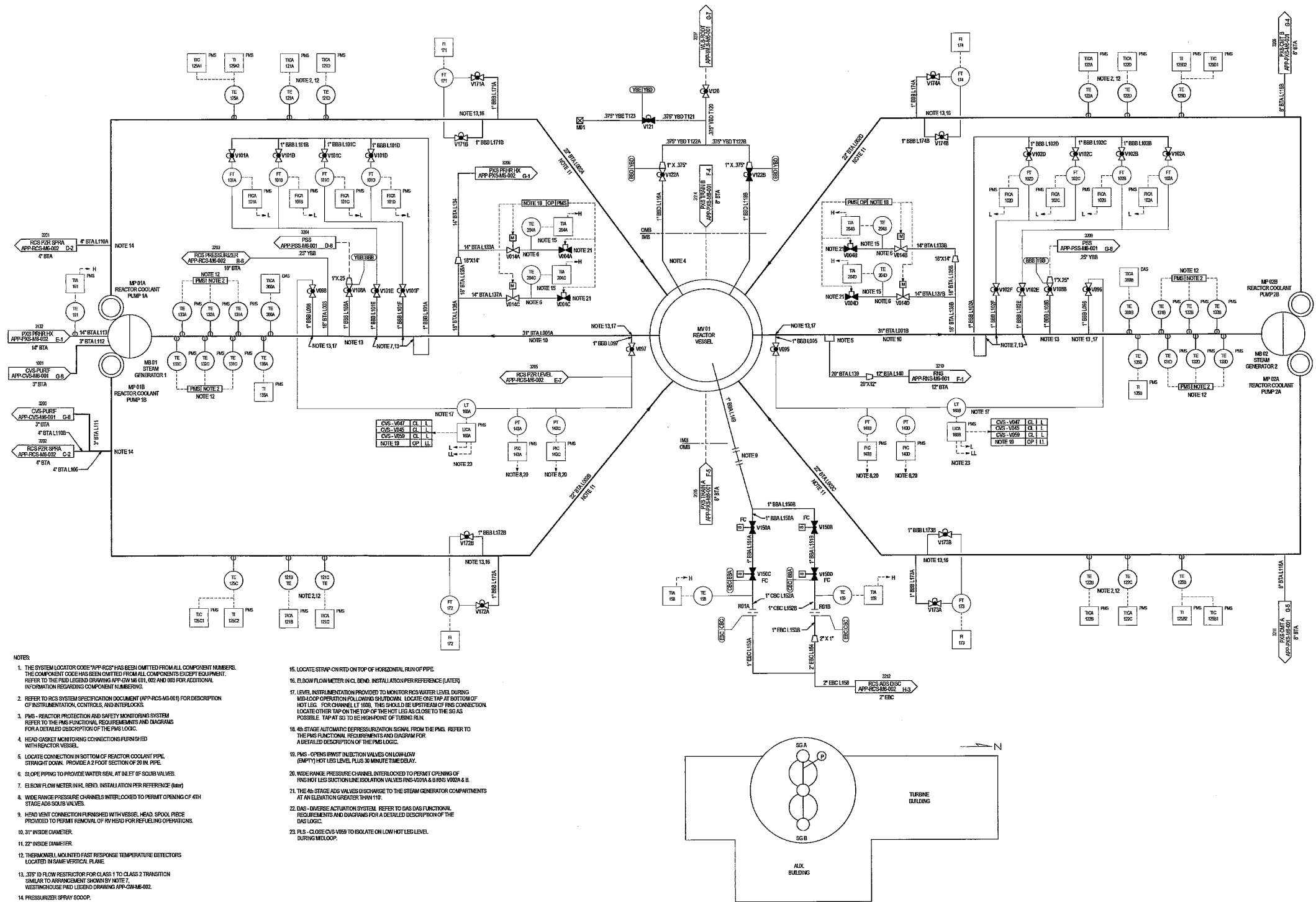


Figure 5.1-4

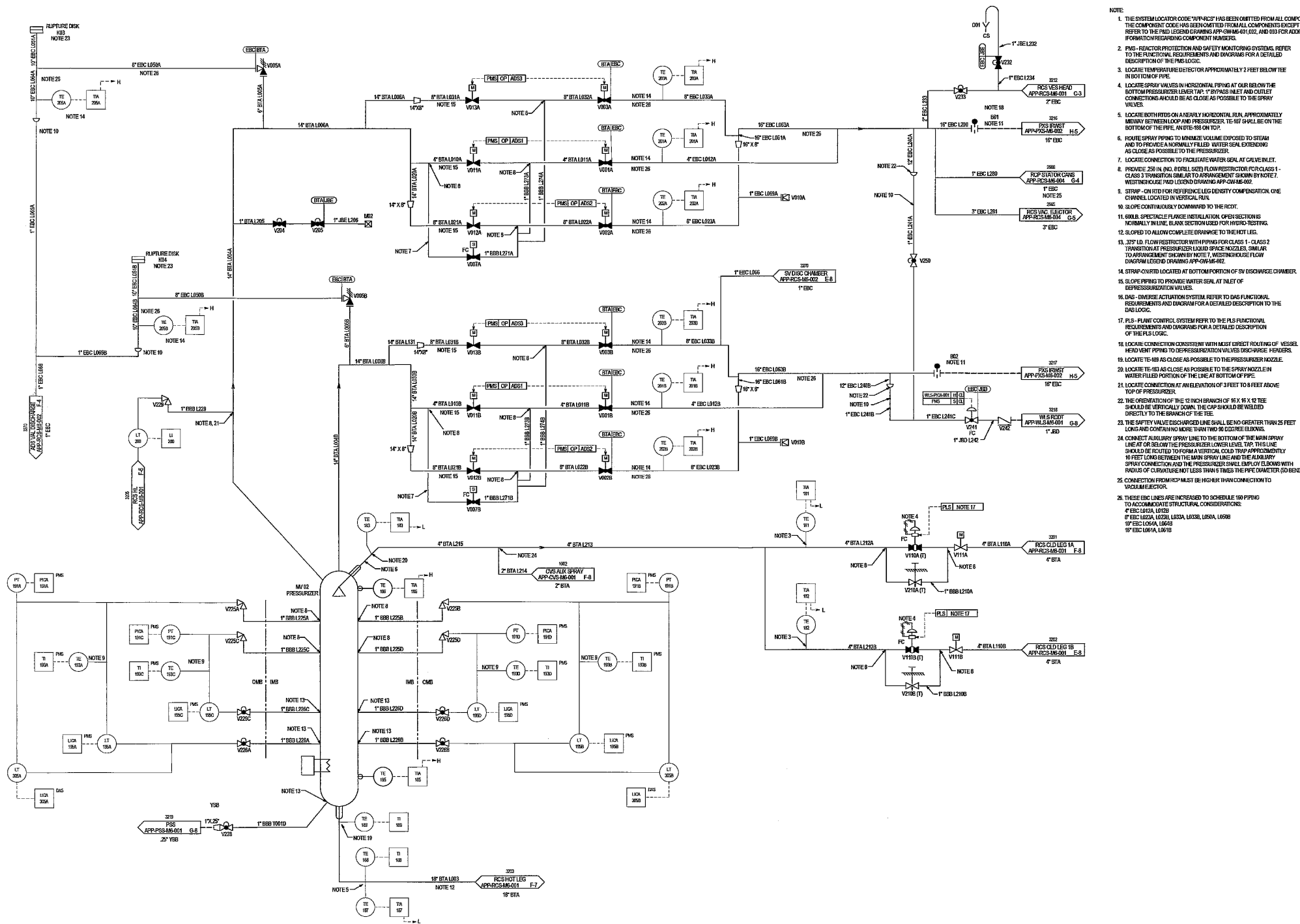
Reactor Coolant System – Elevation

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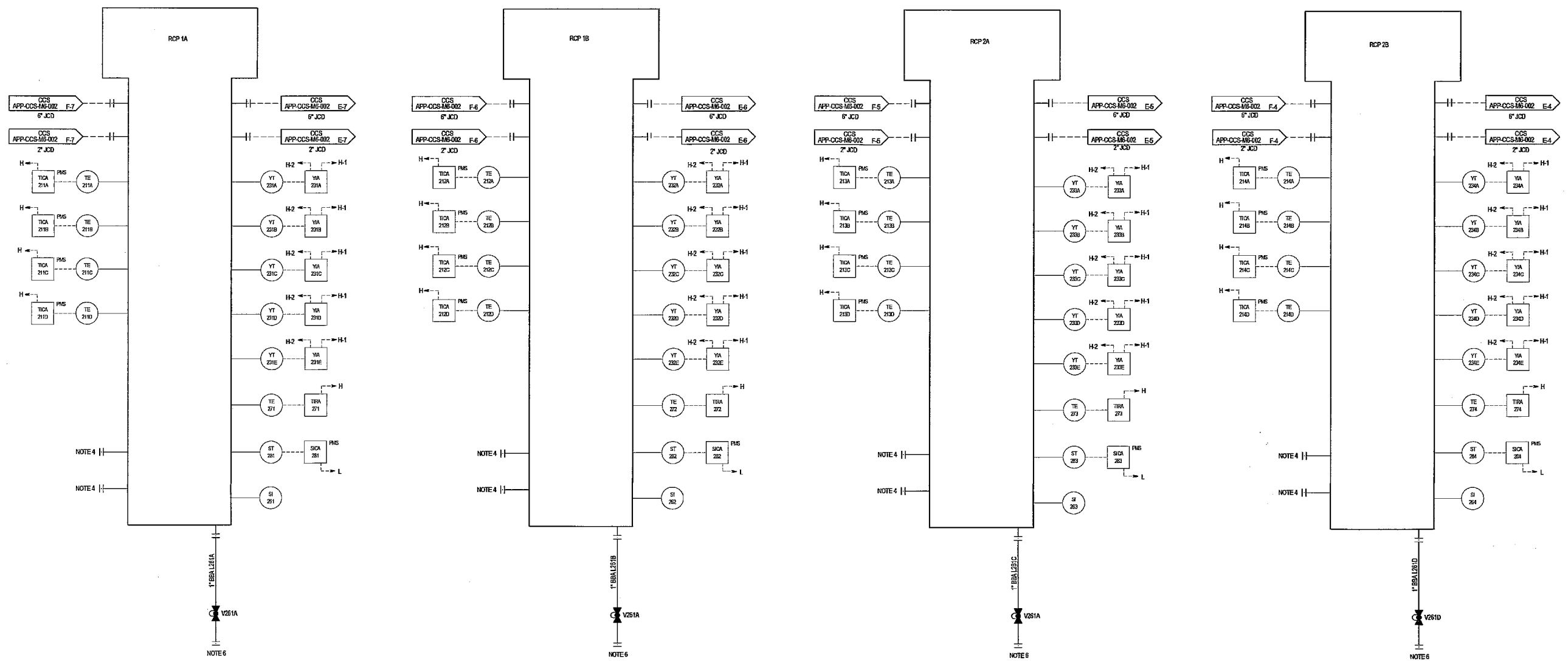
Inside Reactor Containment
Figure 5.1-5 (Sheet 1 of 3)

Reactor Coolant System
Piping and Instrumentation Diagram



Inside Reactor Containment
Figure 5.1-5 (Sheet 2 of 3)

Reactor Coolant System
Piping and Instrumentation Diagram



- NOTES:
1. THE SYSTEM LOCATOR CODE "APP-RCS" HAS BEEN OMITTED FROM ALL COMPONENT NUMBERS. THE COMPONENT CODE HAS BEEN OMITTED FROM ALL COMPONENTS EXCEPT EQUIPMENT. REFER TO THE P&ID LEGEND DRAWING APP-GM-MG-001, 002 AND 003 FOR ADDITIONAL INFORMATION REGARDING COMPONENT NUMBERING.
 2. REFER TO RCS SYSTEM SPECIFICATION DOCUMENT (APP-RCS-MG-001) FOR DESCRIPTION OF ALL INSTRUMENTATION, CONTROLS, AND INTERLOCKS.
 3. PMS - REACTOR PROTECTION AND SAFETY MONITORING SYSTEM. REFER TO THE PMS FUNCTIONAL REQUIREMENTS AND DIAGRAMS FOR A DETAILED DESCRIPTION OF THE PMS LOGIC.
 4. INSTALL BLIND FLANGE ON CONNECTION FROM STATOR CAN USE FOR VACUUM FILL. CONNECTION ON SHEET 4.
 5. TE-211A-D, TE-212A-D, TE-213A-D, TE-214A-D, TE-271-274, ARE SENSOR SUPPLIED WITH THE REACTOR COOLANT PUMP. YI-231A-E, YI-232A-E, YI-233A-E, YI-234A-E, ST-281-284, ST-285-288 ARE SENSOR NOT SUPPLIED WITH THE REACTOR COOLANT PUMP.
 6. CONNECTIONS PROVIDED FOR TEMPORARY FLUSHING.

Inside Reactor Containment
Figure 5.1-5 (Sheet 3 of 3)

Reactor Coolant System
Piping and Instrumentation Diagram